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REPORT DOCUMENTATION PAGE

AD-A214 097

1a.	1b. RESTRICTIVE MARKINGS
2a.	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 23397.14-EL
6a. NAME OF PERFORMING ORGANIZATION Dept. of Elec. & Comp. Engr. Univ. of Mass/Amherst 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Amherst, MA 01003	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING / SPONSORING ORGANIZATION U. S. Army Research Office 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAL03-86-K-0087
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
A STUDY OF INTER-INJECTION-LOCKED PHASED ARRAYS

12. PERSONAL AUTHOR(S)
Stephan, Karl D.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 860801 TO 890731	891010	25

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Injection locking; quasioptics; power combining; phased arrays; coupled oscillators,

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A study of phased arrays driven by individual active solid-state devices has led to a number of interesting and potentially useful discoveries. It was found that the phases of a number of oscillators, if coupled together properly, can be controlled by means of only one master source and phase shifter. In addition to this experimental demonstration, power combining of planar oscillators in a quasioptical cavity was demonstrated and several effects of coupled oscillators were explored. Finally, the potential of resonant-tunnelling-diode oscillators as self-oscillating mixers was investigated.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

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A STUDY OF INTER-INJECTION-LOCKED PHASED ARRAYS

Final Report

by

Karl D. Stephan

October 10, 1989

U.S. Army Research Office

Contract No. DAAL03-86-K-0087

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Table of Contents

I. Introduction

Progress in monolithic fabrication of microwave integrated circuits has led to reduced size and weight as well as improved performance of many microwave systems. At the shorter microwave and millimeter wavelengths, however, currently available solid-state devices often fail to deliver the required amount of power, so innovative power-combining schemes are still needed. As phased array technology advances, it is desirable to realize such arrays in as simple a manner as possible consistent with performance goals.

These issues stimulated the investigations to be described in this report, and the results can be classified into three areas: (1) interinjection-locked systems, (2) quasioptical power combining, and (3) resonant-tunnel-diode investigations for future use in integrated systems. Before going into detail, we will summarize the specific problems addressed and the results in each of these areas.

The term interinjection-locking was coined by the author to describe the process of interaction among a system of coupled oscillators which results in phase coherence throughout the system. The usual method of delivering controlled-phase microwave power to an array of antennas involves phase-matched power distribution networks and directly controlled phase-shifting circuits. Although these system show outstanding performance when properly designed, their complexity makes them bulky and expensive. The interinjection-locking technique developed under this program controls the phases of several oscillators solely by means of mutual coupling. In the work to be described, a four-element steerable phase array was successfully demonstrated at 10 GHz. All four phases at the antennas were controlled by only one phase shifter, and power from each antenna's oscillator was combined spatially rather than by a circuit network. The simplicity of the system should be attractive to designers working in the higher frequencies where available power per device is low and losses in available phase shifters are high. Other experiments performed at 10 GHz and 35 GHz dealt with various aspects of mutual coupling between two oscillators. Although less interesting from an applied viewpoint,

these investigations elucidated some coupled-oscillator effects that need to be understood thoroughly before further progress in this area is made.

The second area of research involved quasioptical power combining. This topic is a broad one since, strictly speaking, every phased array combines power quasioptically. A more specific definition applies to power-combining techniques which use free space and optical components such as mirrors or lenses, rather than conventional guided-wave media such as waveguide or microstrip. A particularly attractive method of quasioptical power combining involves the use of a Fabry-Perot type of open resonator. We have explored details of the coupling mechanisms between planar structures used in microwave integrated circuits and microwave open resonators. Although large numbers of devices have yet to be used in such a technique, experiments with one or two oscillators in a cavity have shown encouraging results, and a theory of microstrip-to-open-resonator coupling has been developed and verified experimentally.

The third topic of inquiry concerns a relatively new device, the resonant tunnelling diode or RTD. The resonance referred to is a quantum-mechanical effect which allows a negative-resistance characteristic to be obtained at very high frequencies. The RTD's potential for power generation and signal processing in the upper millimeter-wave range is encouraging, since oscillations above 400 GHz have been obtained from these devices. The relatively low power obtainable from a single RTD makes them more attractive for receiving than transmitting applications, and it is possible that power combining will be needed even if the devices are used to drive a receiving mixer. The potential for such use has been evaluated by us in a study of a 1-GHz self-oscillating RTD mixer, and some previously unpublished work on this topic will be briefly reviewed here. This report will conclude with lists of publications and personnel.

II. Interinjection-Locked Systems

A. Two-Oscillator Studies

The earliest record of what is now known as injection locking was made by C. Huygens (1629–1695), who noted that two pendulum clocks of similar make would fall into synchronism if mounted on a thin wooden board [1]. The same effect would not occur if they were attached to a solid masonry wall, showing that the coupling of vibrations between the mechanical oscillators was somehow responsible. Many workers in the field of electrical engineering such as Adler [2], Schlosser [3], and notably Kurokawa [4] have studied various aspects of this problem in various degrees of detail. In our efforts to discover ways of encouraging mutual injection locking of oscillators, we decided initially to study the simplest possible system: two oscillators.

We began by designing a microstrip-resonator oscillator using a Gunn diode as the active element. This choice was based on the desire to adhere as much as possible to fabrication techniques compatible with monolithic integration. Once two such oscillators were built, it was found that the microstrip line was a reasonably efficient antenna, and that the oscillators could be coupled by means of radiation alone.

In a system of N coupled oscillators, there are N possible normal modes of oscillation. A mode is simply a definite amplitude and phase relationship among the oscillating elements of a system. Linear mechanical systems exhibit what are called normal modes, and any number (up to N) of normal modes can exist simultaneously in such a system. In a system of identical oscillators that are weakly coupled, the normal modes will each have a characteristic frequency not too far from the free-running frequency of one isolated oscillator.

Consider the pair of mass-and-spring oscillators coupled by a third central spring in Fig. 1. The two normal modes of this system are the in-phase mode (a) in which the masses move together as a unit, and the out-of-phase mode (b) in which the masses move

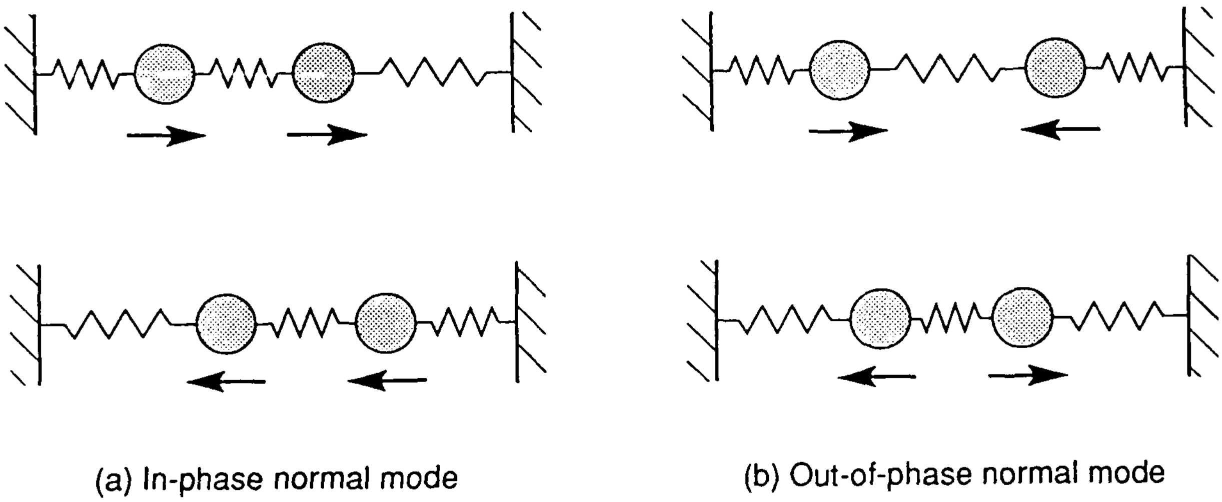


Fig. 1. Normal modes of two-element coupled mechanical oscillators.

as mirror images of each other. Any sustained periodic motion of the two masses will be a linear combination of these two modes, which in general will be at different frequencies.

Once a nonlinear element is included, as in the microstrip Gunn-diode oscillators just described, the picture changes. As long as the nonlinearities are reasonably well-behaved, it is still true that N coupled oscillators allow N normal modes to occur. However, the nonlinearity now introduces the issue of stability. Although a given mode may be possible in the mathematical sense (meaning that once it is set up it will go on forever) it may not be stable, that is, it may not recover from small perturbations due to noise, for example. Physically, if a mode is unstable, the system quickly shifts over to a stable mode. For this reason, many nonlinear systems of coupled oscillators typically operate in only one stable single-frequency mode. This situation is desirable from a power-combining point of view since phase coherence is a prerequisite to efficient power combining.

Just as in the case of the mechanical oscillator of Fig. 1, the two possible modes of the pair of coupled oscillators in Fig. 2 can be determined by symmetry. The equivalent circuits shown model the Gunn-diode nonlinearity by means of a negative conductance $-G_D$. The microstrip patches are modelled by the $G_L - L - C$ tank circuit, and the radiating part of the antennas are modelled as A_1 and A_2. If we assume that the oscillators are identical, the only two possible modes for the two-oscillator systems are shown in Fig. 3. Because of the symmetry involved, the two modes can be separated and analyzed for the admittances Y_e and Y_o that each mode presents to the nonlinear diode. These admittances will vary with the separation distance d, so the behavior of the system was studied as the two oscillators were moved apart.

The results are shown in Fig. 4, which is reproduced from our Ref. [5]. The upper graph (a) in Fig. 4 is a plot of phase versus frequency, and essentially monitors which mode (even or odd) is present. A phase difference near 0^o indicates the even mode, while a difference near 180^o signifies the odd mode. A clear periodicity is evident: the stable mode switches from even to odd and back every wavelength. The reason for this behavior will

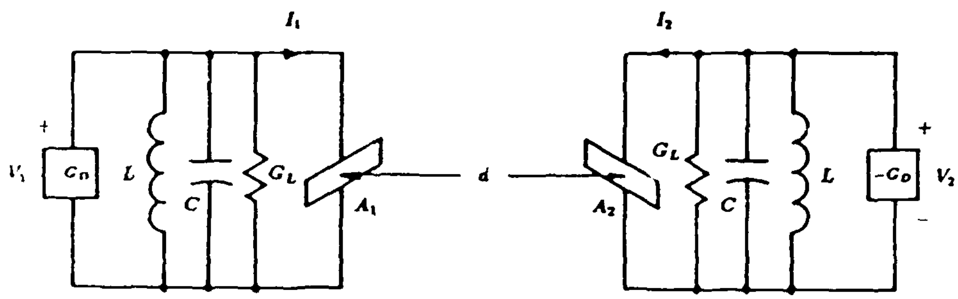


Fig. 2. Microstrip oscillator equivalent circuit models.

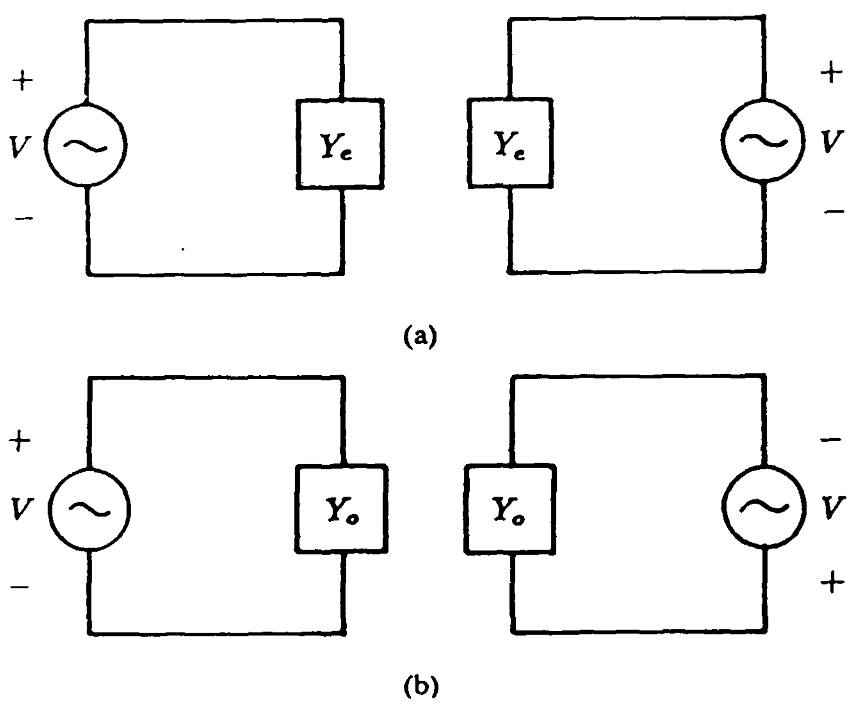


Fig. 3. Oscillators of Fig. 2 treated by even-odd mode analysis: (a) even mode; (b) odd mode.

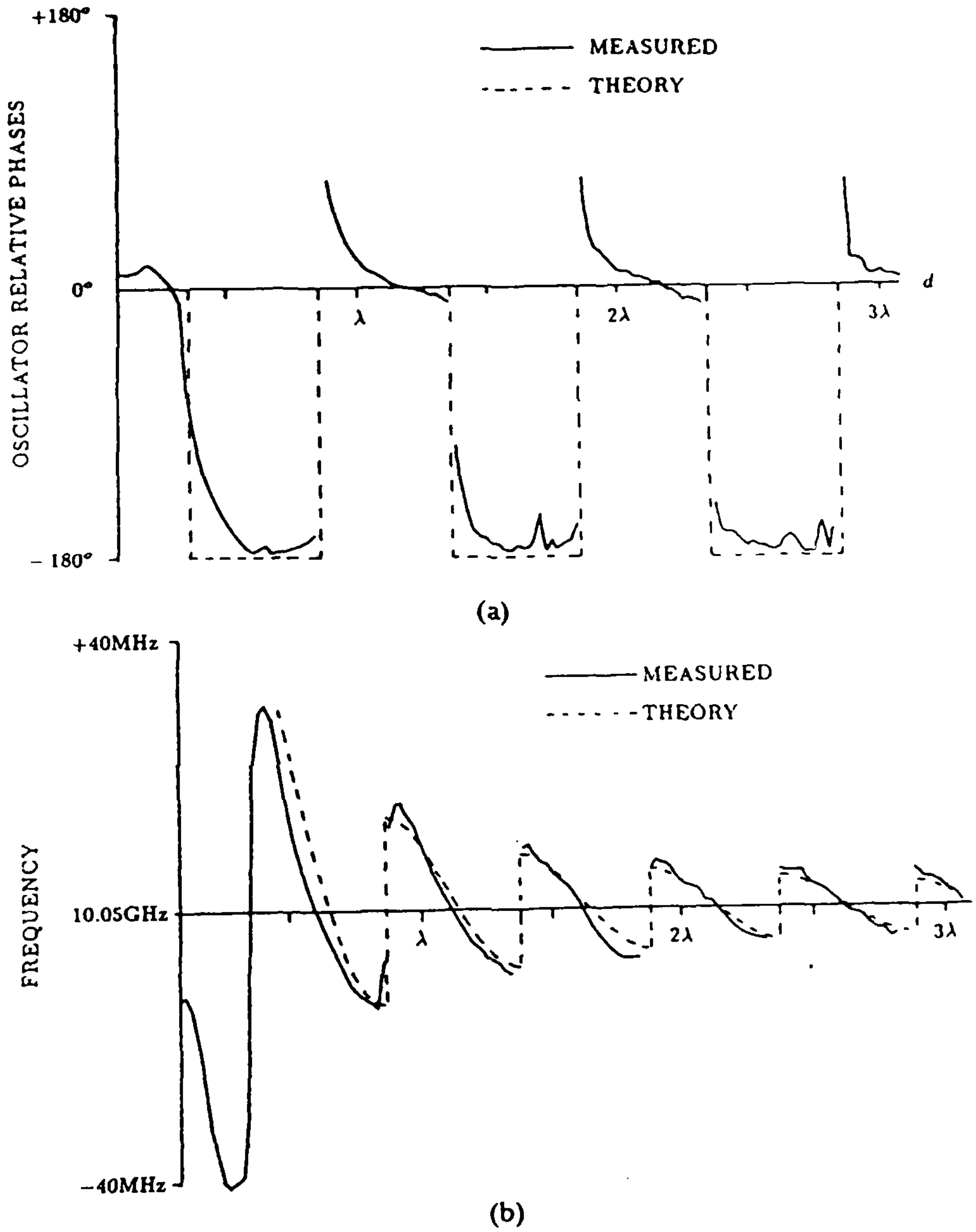


Fig. 4. Coupled oscillator measured and theoretical (a) phase and (b) frequency versus separation *d*.

be discussed below. Along with the phase changes, the synchronized frequency versus the distance plot looks like a damped sine wave whose phase is inverted every half cycle. This is because the coupling that produces a frequency minimum for the even mode will produce a frequency maximum for the odd mode and vice versa. The smooth variation of frequency versus distance is thus discontinuously interrupted whenever the system changes modes, as the data shows.

Why does the stable mode alternate between even and odd? This is a radically nonlinear phenomenon, and results from the variation in the real (conductance) part of Y_e and Y_o. Simply put, the nonlinear elements favor that mode which minimizes the dissipation in the system. This rule has been proved for lumped-element systems of certain kinds [6], and is probably true for a wide variety of physical systems. As the separation increases, the admittance showing the smallest conductance alternates between Y_e and Y_o with a period of one wavelength and so does the phase relationship between the two oscillators. The nonlinear devices "lazily" choose the mode which results in the least power dissipation, giving the results shown.

In a related experiment at 35 GHz involving two coupled Gunn oscillators, we investigated the injection-locking range of the synchronized pair using a third injection-locking source. We found a significant difference in the frequency range over which injection locking occurred between the even and the odd modes, and developed a qualitative theory to account for it. Further details are given in Ref. [7]. The most practical discovery from this series of experiments was that a pair of oscillators could be coupled through a suitable phase delay (free space in this case) so that they would operate in the desirable synchronized mode.

B. Larger Interinjection-Locked Systems

The initial idea of controlling the phases of several mutually coupled oscillators with one phase shifter was developed by the author prior to the beginning of this program [8]. However, once the program began, much more extensive theoretical and experimental

work was initiated. Progress on the theoretical front involved an extension of Kurokawa's injection-locking model to the case of an arbitrary number of oscillators linked to a passive network. This theoretical framework was used to design some hypothetical 4-by-4 element phased arrays controlled by eight or twelve phase-controlled driving sources. For example, we found that by choosing the drive phases shown for the 4×4 array of Fig. 5, we could not only obtain a coherent output beam but could also steer it 5.5^{o} away from boresight (perpendicular to the array plane). The network also showed a measure of robustness, for when one oscillator was "disabled" (its output in the computer model set to zero), the remaining oscillators showed a relatively small phase change and the array pattern was not degraded significantly. These computer studies [9] demonstrated that there were no obvious mathematical stumbling blocks in the path leading to experimental realization of an interinjection-locked microwave phased array.

Accordingly, we proceed to prove the concept with a four-element experimental system built with 10-GHz Gunn-diode oscillators as sources [10]. The test system's block diagram is shown in Fig. 6, including the single phase shifter used to control all four oscillator phases. Coupling between oscillators was by means of a prescribed length of microstrip line. The experimental verification of this phase control is illustrated in Fig. 7. Each oscillator was then connected to an antenna and array patterns were measured for extreme right, boresight, and extreme left phase steering. The measured patterns of the system are shown in Fig. 8. Because the phase progression from one oscillator to the next in such a system has a theoretical limit of $\pm 90^{o}$ (and a practical limit of about $\pm 60^{o}$), very wide scan angles cannot be obtained with this technique. However, for specialized applications such as conical scanning the method may prove to be entirely adequate.

To summarize the results of the interinjection-locking phase of this investigation, we developed a number of theoretical tools to treat the case of two or more oscillators coupled electromagnetically. The essential features of the theories were verified in several

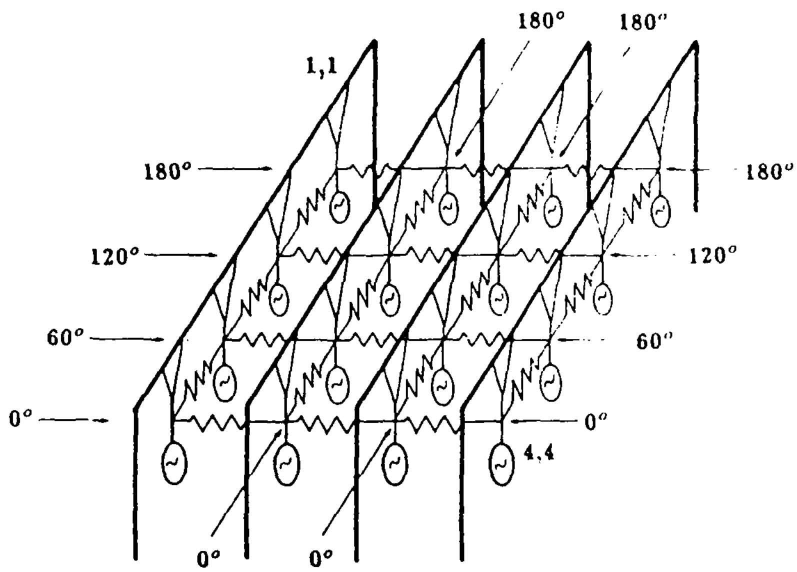


Fig. 5. 4-by-4 interinjection-locked phased array with twelve control phases to produce 5.5° beam steering.

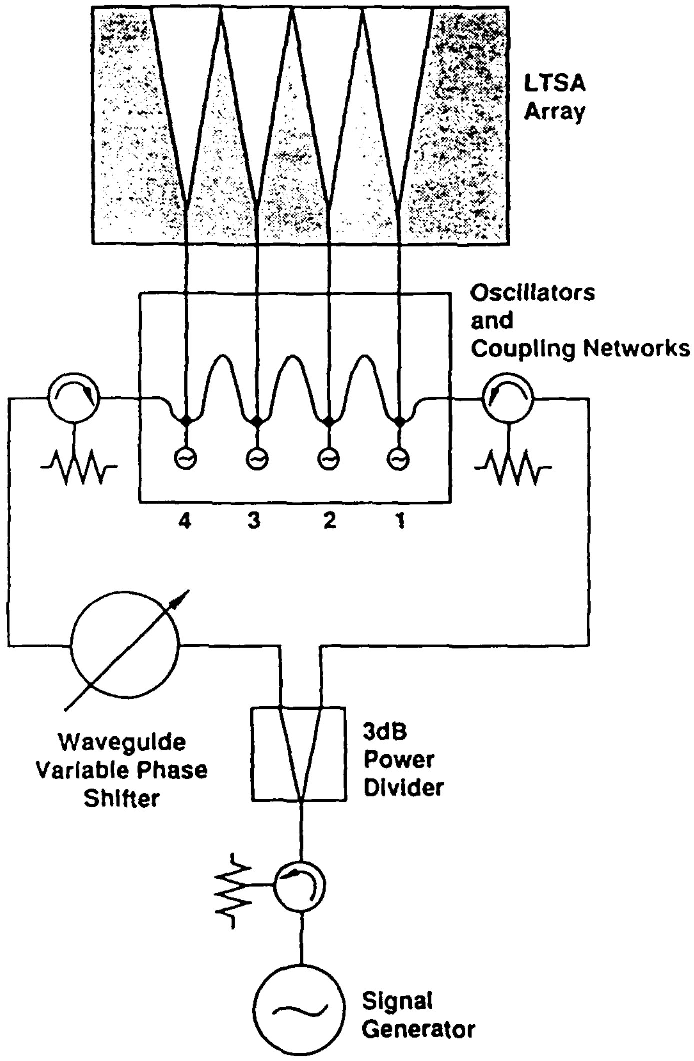


Fig. 6. Block diagram of four-element experimental interinjection-locked phased array at 10 GHz.

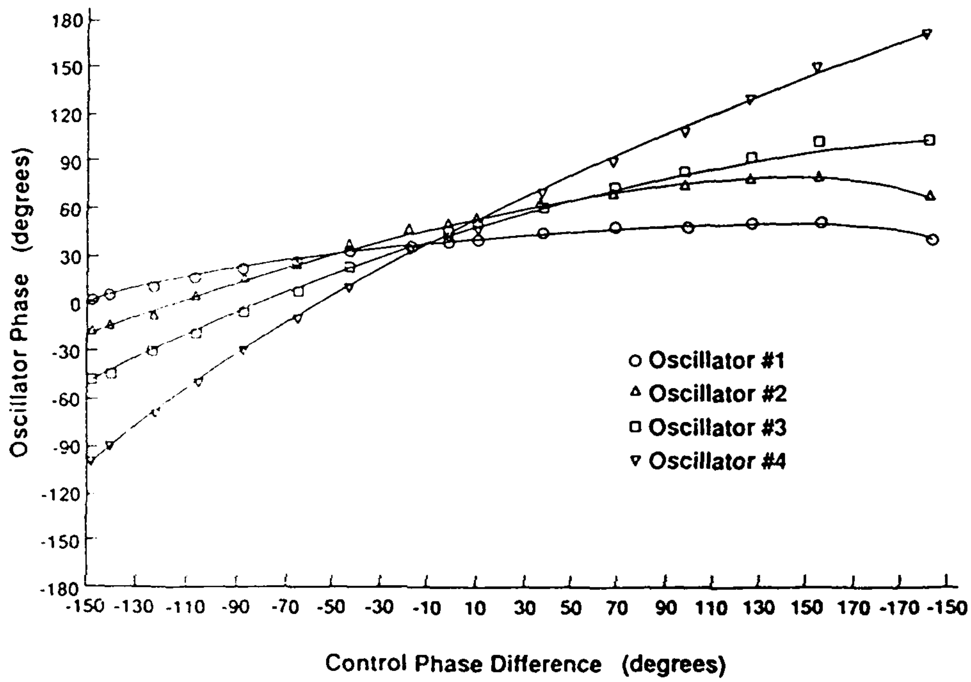


Fig. 7. Oscillator output phase versus injected control phase difference.

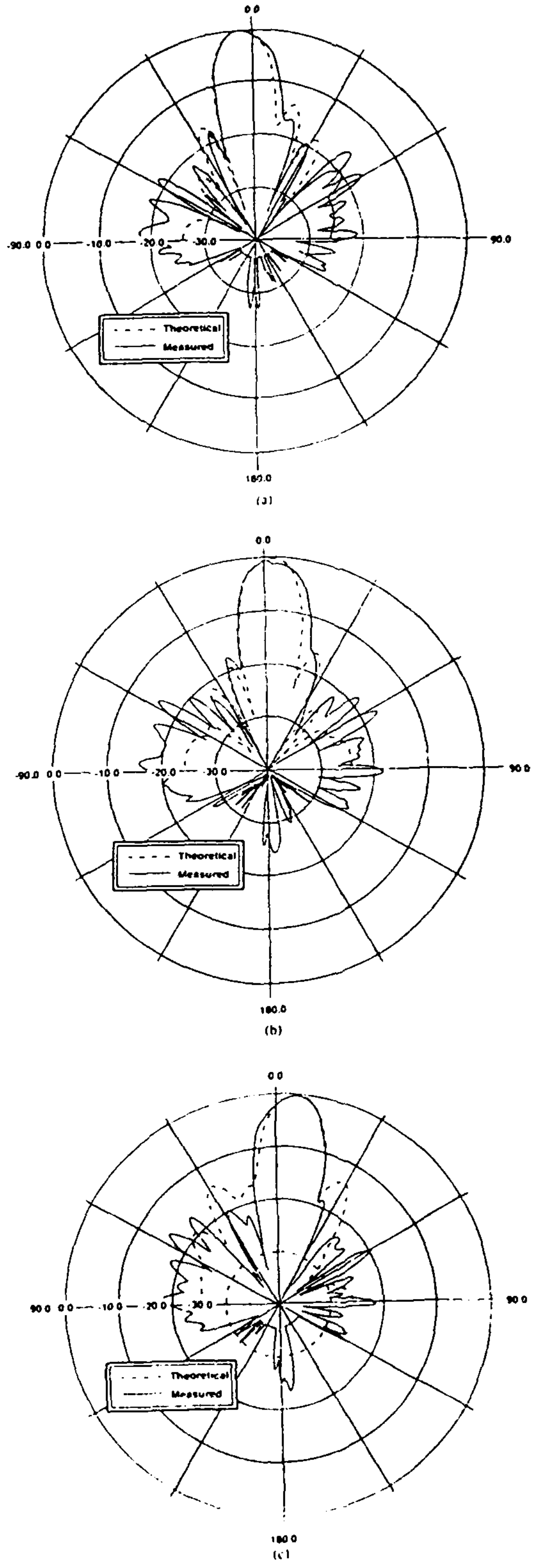


Fig. 8. Theoretical and measured array patterns for (a) left, (b) boresight, and (c) right beam steering of phased array.

experiments, culminating in the construction and successful testing of a four-element interinjection-locked phased array at 10 GHz.

III. Quasioptical Open-Resonator Power Combining

An important feature of any oscillator system is energy storage in a resonant structure or structures. The interinjection-locked systems discussed in Part II stored most of their high-frequency energy in the individual oscillators' resonant circuits, usually sections of microstrip line. While this represents the ultimate in simplicity, the limitations of physically small microstrip resonators are well known: low Q, consequently relatively low efficiency, and poor spectral characteristics of the associated oscillators. When Mink [11] proposed in 1986 a method of using a quasioptical cavity as a means of combining power from several solid-state oscillators, the salient issue was efficiency. While the high efficiency that his technique promises remains as yet unrealized because of the practical problems of fabricating the large number of uniform elements required, we have carried out a number of experiments involving one or two oscillators in a quasioptical cavity at frequencies ranging from 10 to 50 GHz. Although some indications of good combining efficiency have been found, an added advantage of operating a planar oscillator coupled to an open resonator is that the very high Q of the resonator vastly improves the noise sidebands of the oscillator. While it is true that below 30 GHz such improvements can be obtained with much greater mechanical convenience by means of a small dielectric resonator, "clean" sources are increasingly difficult to obtain in the higher millimeter-wave range, where quasioptical components take on practical sizes. The discussions to follow will treat the 10 GHz and the 50 GHz experiments in turn.

A. 10 GHz Quasioptical Power Combining and Stabilization

Before a well-founded experimental program could begin, it was necessary to establish a theoretical treatment of the coupling between planar circuit elements and the fields in an open resonator. Although Mink's treatment [11] did this in principle, his idealized current elements were simpler than the actual current propagating on a microstrip

line. We undertook an analysis that assumed the microstrip currents propagated in the normal way and took into account the significant effects of phase delay along the line. Simultaneously we began experimental investigations of coupling effects, using a 15-cm gold-plated spherical mirror and a simple two-port microstrip on a ground plane (see Fig. 9). Experimentally we found that when the Gaussian beam of the open resonator was centered on the microstrip line, the resonator absorbed power from the line and produced a transmission dip as shown in Fig. 10, which is from our Ref. [12]. Further experiments, guided by a rather complete theoretical treatment, showed that two widely separated short open-ended microstrip lines could be coupled by an open-resonator mode with as little as 0.8 dB loss [13].

These passive-circuit developments reinforced the experiments with two microstrip-resonator Gunn-diode oscillators which we had performed at about the same time. These experiments are described in Ref. [14], and involved the same kind of planar oscillators discussed earlier. They proceeded in two steps. In the first step, we used an interdigitated planar coupler to optimize the output power from each oscillator independently, without a quasioptical open resonator. Only 2-3 mW was obtainable from each circuit. Then, the pair of oscillators was mounted on a flat ground plane which formed one reflector in a Fabry-Perot resonator, the other reflector being the spherical mirror described above. This configuration is shown in Fig. 11. The maximum power coupled out through the Gaussian-beam mode of the open resonator was 13.3 mW, more than twice the power obtainable from a planar combining arrangement. Experiments with a single planar-output oscillator also revealed the high degree of frequency stabilization that an open resonator can produce. Fig. 12 shows the spectral improvement obtained when the spherical mirror is adjusted to lock the oscillator onto one of the resonator's TEM modes.

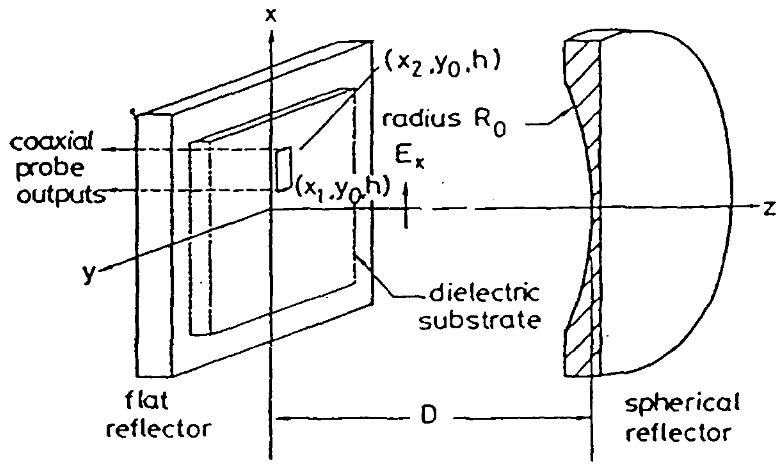


Fig. 9. Experimental investigation of interaction between microstrip and open-cavity resonator.

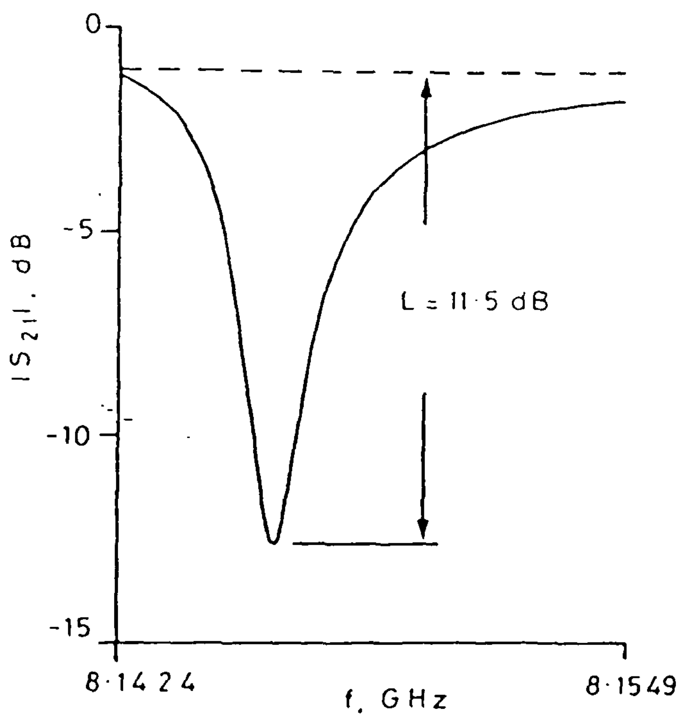


Fig. 10. Transmission versus frequency of microstrip line coupled to a quasioptical open resonator.

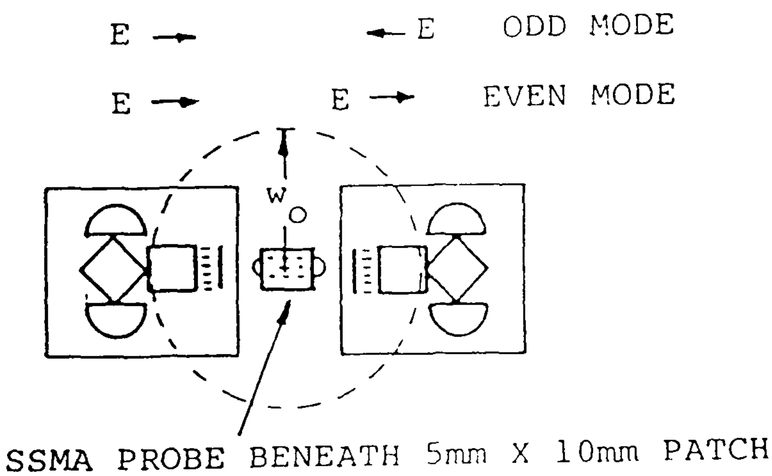


Fig. 11. Two planar oscillator inside beam waist of radius ω_0 with central coupling patch for output of quasioptical power combining experiment.

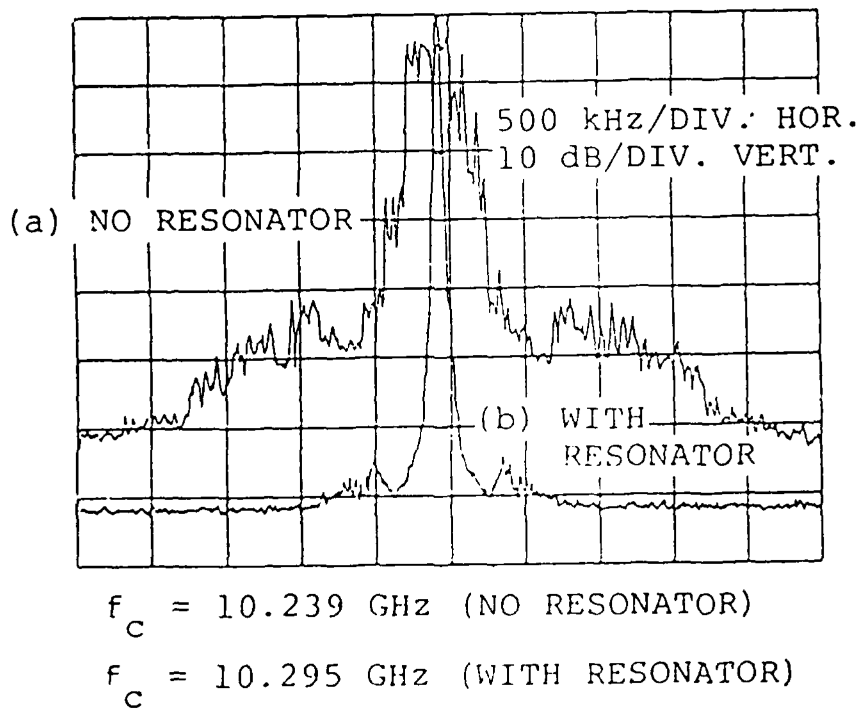


Fig. 12. Output spectra of planar oscillator: (a) No open resonator; P_{out} = 2.1 mW (b) With open resonator; P_{out} = 1.7 mW.

B. 50 GHz Quasioptical Oscillator Stabilization

In a productive collaboration with Burhan Bayraktaroglu of Texas Instruments Inc., we have had the privilege of using monolithic IMPATT oscillators designed to operate in the 50 GHz region. These devices are described adequately elsewhere [15], so only a brief treatment will be given here. A single oscillator consists of two IMPATT diodes coupled by means of air or silicon nitride bridges to a half-wave microstrip line on semi-insulating GaAs. The entire circuit is monolithically integrated. We found that by mounting one of these oscillator chips in the manner shown in Fig. 13, we were able to lock the oscillator's output to the TEM_{005} mode of the tunable cavity over a 400 MHz range. This cavity was formed with a 5-cm diameter copper mirror at the end of a brass cylinder, so it has very practical dimensions allowed by the short operating wavelength. Once the oscillator was stabilized by the cavity mode, we once again obtained a considerable improvement in the spectrum as Fig. 14 shows.

Experiments were continuing at the termination date of this program to operate more than one oscillator in the cavity, and these efforts will continue under the newly funded program.

IV. Resonant Tunnelling Diode Mixer Experiments

Before much work is put into power combining of RTDs, one should ask whether the power obtained will be usable in terms of spectral characteristics. Since RTDs are not yet available commercially, we embarked on a collaborative effort with Prof. Kei May Lau of the University of Massachusetts at Amherst and Prof. Erik Kollberg of Chalmers University, Gothenburg, Sweden. Prof. Lau grew the required quantum wells in her organometallic chemical vapor deposition system, and members of Prof. Kollberg's group processed the material into large-area diodes. The resulting devices were not state-of-the-art quality in terms of series resistance and cutoff frequency. Nevertheless, we found that they were usable in an integrated self-oscillating mixer circuit operating at about 1 GHz, near the cutoff frequency of the diode.

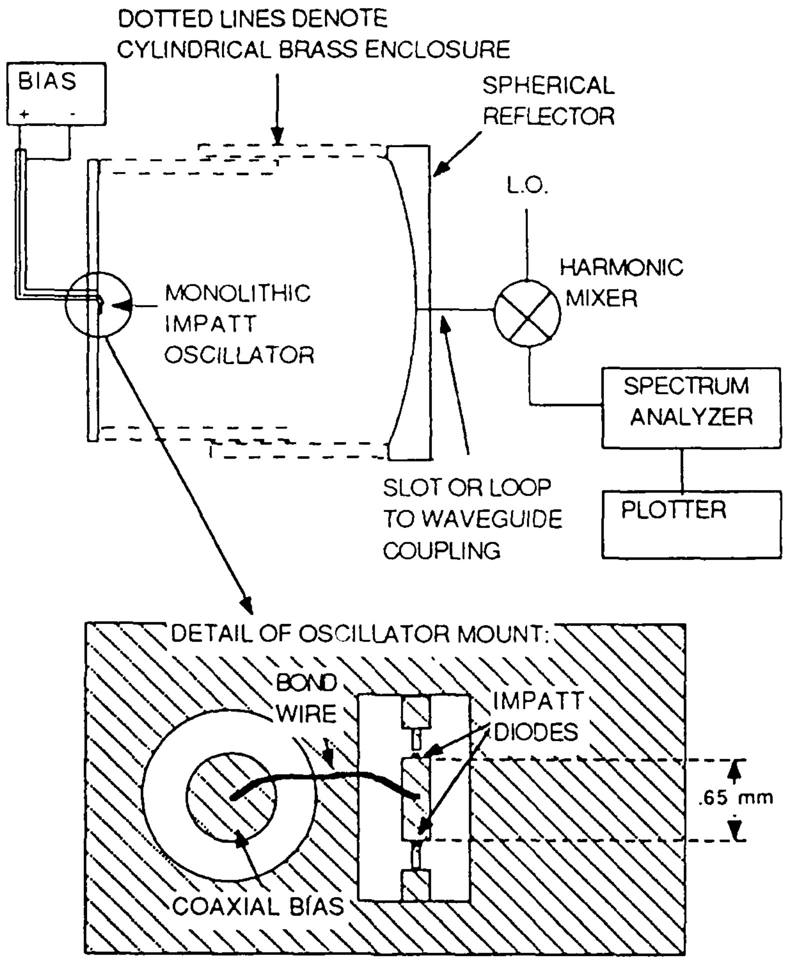
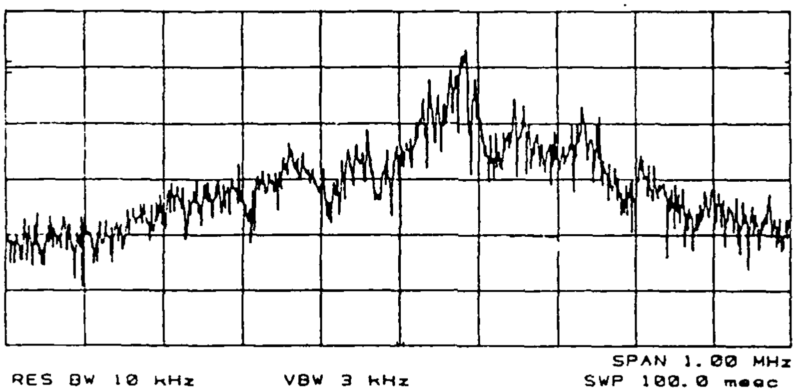
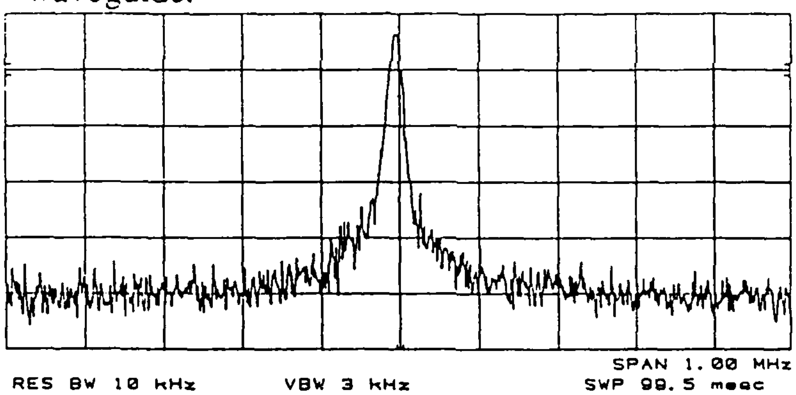


Fig. 13. Quasioptical cavity resonator containing monolithic IMPATT oscillator chip.



(a) Monolithic IMPATT oscillator spectral response at f_0=56.031 Ghz while operating directly into waveguide.



(b) Monolithic IMPATT oscillator spectral response at f_0=56.097 Ghz while operating in the closed quasi-optical cavity.

Fig. 14. Monolithic IMPATT oscillator spectrum (a) without and (b) with quasioptical cavity stabilization.

A particularly important feature of this mixing circuit is its noise figure. To our knowledge no one has published noise figure data for a self-oscillating RTD mixer, and so in our studies we concentrated on this aspect of the circuit's performance. Since an RTD is a negative-resistance device with an output impedance at IF that can have a negative real part, it was necessary to go beyond the conventional noise figure definitions to a concept popularized by Weinreb called exchangeable power [17]. Using this concept, we were able to obtain meaningful and repeatable noise figure data for the RTD self-oscillating mixer. The best single-sideband result was a somewhat disappointing 23.7 dB, but we plan further investigations into the physical processes leading to this rather high figure.

V. Conclusions

The topics investigated cover a rather broad area, but we wish to reiterate the substantial advances in both theoretical and experimental aspects of the problems dealt with. These can be summarized as:

(1) First demonstration of quasioptical open-resonator power combining of planar microwave oscillators.

(2) First analysis of microstrip coupling to a quasioptical open resonator mode.

(3) First demonstration of a four-element beam-steerable interinjection-locked phased array.

(4) First demonstration of monolithic IMPATT oscillator quasioptical cavity stabilization.

(5) First accurate measurements of RTD self-oscillating mixer noise figure.

VI. List of Publications Under A.R.O. Sponsorship

A. Journal Publications

1. "An X–band experimental model of a millimeter–wave interinjection–locked phased array system," by W.A. Morgan, Jr. and K.D. Stephan, IEEE Trans. on Antennas and Propagation, vol. 36, pp. 1641—1645, Nov. 1988.

2. "Microstrip circuit applications of high-Q open microwave resonators," by K.D. Stephan, S.L. Young, and S.C. Wong, IEEE Trans. on Microwave Theory and Tech., vol. 36, pp. 1319–1327, Sept. 1988.

3. "Mode determination of planar coupled millimeter–wave oscillators by quasioptical injection locking," by K.D. Stephan and S.L. Young, Microwave and Optical Technology Letters, vol. 1, pp. 156–160, July 1988.

4. "Mode stability of radiation–coupled interinjection–locked oscillators for integrated phased arrays," by K.D. Stephan and S.L. Young, IEEE Trans. on Microwave Theory and Tech., vol. MTT–36, pp. 921—924, May 1988.

5. "Open cavity resonator as high–Q microstrip circuit element," by K.D. Stephan, S.L. Young, and S.C. Wong, Electronics Letters, vol. 23, pp. 1028–1029, Sept. 1987; also erratum, v. 23, p. 1397, Dec. 1987.

6. "Analysis of inter–injection–locked oscillators for integrated phased arrays," by K.D. Stephan and W.A. Morgan, Jr., IEEE Transactions on Antennas and Propagation, Vol. AP–35, pp. 771–781, July 1987.

B. Conference Papers, etc.

1. "Quasioptical microwave and millimeter–wave power combining," by K.D. Stephan and S.L. Young, SPIE (vol. 947) Conf. on Interconnection of High Speed and High Frequency Devices and Systems, Newport Beach, CA, March 1988.

2. "The open-cavity millimeter-wave resonator as a high–Q microstrip circuit element," by K.D. Stephan and S.L. Young, Digest of the Twelfth International Conference on Infrared and Millimeter Waves, p. 42, Lake Buena Vista, Fla., Dec. 1987.

3. "Inter–injection locking — a novel phase control technique for monolithic phased arrays," by W.A. Morgan, Jr. and K.D. Stephan, Digest of the Twelfth International Conference on Infrared and Millimeter Waves, pp. 81–82, Lake Buena Vista, Fla., Dec. 1987.

4. "Stabilization and power combining of planar microwave oscillators with an open resonator," by S.L. Young and K.D. Stephan; 1987 IEEE Int'l. Microwave Symp. Dig., pp. 185–188, Las Vegas, Nev., June 1987.

5. "Radiation coupling of inter–injection–locked oscillators," by S.L. Young and K.D. Stephan; SPIE (vol. 791) Conf. on Millimeter Wave Technology IV and Radio Frequency Power Sources, pp. 69–76, Orlando, Fla., May 1987.

VII. List of Personnel Involved in Investigations under A.R.O Sponsorship

1. Principal Investigator: Karl D. Stephan
2. Co-Investigator: Robert W. Jackson
3. Graduate Students (in chronological order):
   * William A. Morgan
   * Song-Lin Young – M.S., Univ. of Mass, 1988
   * Sai-Chu Wong (M.S. degree expected 1989)
   * William P. Shillue (M.S. degree expected 1989)
   * Chong-Lap Woo (M.S. degree expected 1989)

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[1] N. Minorsky, *Nonlinear Oscillations* (Princeton, New Jersey: D. Van Nostrand, 1962), p. 438.

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